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Single-Shell Tank Waste Retrieval Allowable Vacuum Assessment

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Richland, WA 99352
U.S. Department of Energy Contract DE-AC27-99RL14047

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Abstract: This document provides a documented basis for the allowable vacuum to prevent bottom uplift or buckling of single-shell tank steel liners during waste retrieval activities.

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Single-Shell Tank Waste Retrieval Allowable Vacuum Assessment

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

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Hanford Group, Inc.
Richland, Washington
Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC06-99RL14047

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EXECUTIVE SUMMARY

This engineering analysis documents the results of a study to establish the allowable vacuum to prevent bottom uplift or buckling of steel liner during waste retrieval activities of single-shell tanks (SSTs) located on the Hanford Site near Richland, Washington. Current OSD-T-151-00013 (2002) limits on SST vacuum are too restrictive as the tanks approach empty during waste retrieval. A summary of the SST liner design parameters is provided in Table 1. Buckling or uplift of the dished bottom and cylindrical sidewall portions of the carbon steel liners are investigated for each of the twelve SST tank farms taking into account predicted losses in liner wall thickness due to general corrosion as given in the Appendix.

The additional vacuum in excess of the self-weight and residual waste to cause uplift of flat bottom tanks (A and AX) or buckling of the dished bottom tanks (all other SSTs) is very small except for the 200-Series SSTs. In general, the buckling of the steel liner due to internal vacuum is elastic and the bottom portion of the liner controls the allowable vacuum when the tank is empty provided that the general corrosion of the sidewall portion of the liner is not significantly greater than that of the bottom portion of the liner. This is not always the case if the predicted high corrosion loss for the liner sidewall of some SSTs is realized.

However, buckling of the sidewall liner may be precluded by air leakage between the waste storage space and the interface between the liner and the concrete wall. Although the lead flashing at the top of the liner is provided to prevent condensate from running down between the liner and the concrete wall, it does not necessarily provide an airtight seal to the wall region. Even if the sidewall liner did buckle, it is of less concern during retrieval because it would not likely lead to leakage of the remaining waste. Local buckling would occur between the circumferential stiffeners above the waste level. The post-buckled deformation would be self-limiting because it would likely lead to air leakage between the tank storage space and the liner-concrete interface, thus equalizing the pressure on the liner sidewall. In the case of the bottom portion of the liner, air leakage between the waste storage space and the bottom liner interface to the concrete foundation cannot be assured because the weight of the liner sidewall would tend to seal the bottom region of the liner from the waste storage air space.

Discounting potential buckling of the sidewall portion of the liner, the tank vacuum should be less than the net vacuum pressure to cause buckling of the bottom liner (if dished) plus self-weight pressure of bottom liner plus hydrostatic pressure from waste at bottom of tank but should not exceed 9 inches water gauge (w.g.). Although potential buckling of the liner sidewall has been discounted, the upper vacuum limit (9 in. w.g.) has been retained from current OSD-T-151-00013 to protect the concrete structure. The allowable vacuum for each of the SST tank farms are provided in Table 2 for the min/max range of corrosion wall thickness loss extrapolated conservatively to 2028[1]. For the bottom liner the allowable vacuum is given for an empty tank and for an average waste height of 1, 2, 3, and 4 inches of waste with a specific gravity of 1 and 1.25. The allowable vacuum to prevent sidewall buckling is provided for the lower and upper region of the liner sidewall for information only.

[1] Waste retrieval of all SSTs is scheduled for completion by September 2018, and closure of all SSTs is scheduled for completion by September 2024. The 2028 date was selected to account for potential schedule delays and to provide for additional conservatism in the analysis.

Table 0 summarizes the recommended allowable vacuum for empty tank to prevent buckling or bottom uplift of SST liners.

Table 0. Allowable Vacuum for Empty Single-Shell Tanks.

Tank Farm	Allowable Vacuum (in. w.g.)
100-Series Single-Shell Tanks	
B	1.3
C	0.8
T	1.3
U	0.8
BX	2.4
TX	1.9
BY	1.9
S	2.0
TY	2.0
SX	1.9
A	2.3
AX	2.4
200-Series Single-Shell Tanks	
B, C, T, U	5.3

The allowable vacuum in Table 0 may be increased by the average waste height times the bulk specific gravity of the waste (in. w.g.) but shall not exceed 9 in. w.g.

CHECKLIST FOR INDEPENDENT REVIEW

Document: Single-Shell Tank Waste Retrieval Allowable Vacuum Assessment

Author: LJ Julyk

Yes	No	N/A	
[✓]	[ ]	[ ]	Problem completely defined.
[✓]	[ ]	[ ]	Necessary assumptions explicitly stated and supported.
[ ]	[ ]	[✓]	Computer codes and data files documented.
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[✓]	[ ]	[ ]	Conclusions consistent with analytical results and applicable limits.
[✓]	[ ]	[ ]	Results and conclusions address all points required in the problem statement.

HH Ziada Hassan H. Ziada 9-5-02
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1.0 PURPOSE

Determine allowable vacuum to prevent bottom uplift or buckling of carbon steel liner in single-shell tanks (SSTs) during retrieval operations considering the accumulated corrosion loss of the liner up to time of retrieval.

2.0 BACKGROUND

A total of 149 underground SSTs were constructed between the years 1943 to 1964 with a presumed design life of 25 years. The SSTs are located in twelve separate groupings referred to as tank farms. The twelve tank farms are identified as A, AX, B, BX, BY, and C in the 200 East Area and S, SX, T, TX, TY, and U in the 200 West Area of the Hanford Site near Richland, Washington. The SSTs provide interim storage of high-level radioactive waste until future processing and permanent disposal options become available. There are 133 large capacity (530, 758, and 1,000 Kgal) 100-Series tanks with a 75-foot internal diameter and 16 small capacity (55 Kgal) 200-Series tanks with a 20-foot internal diameter. Four 200-Series tanks were constructed in each of the B, C, T, and U tank farms. Figure 1 shows a schematic of the 100- and 200-Series SST configurations.

The SSTs are steel-lined, reinforced concrete underground waste storage tanks. The steel liner covers the bottom, lower knuckle, and cylindrical sidewall of the concrete structure. Table 1 summarizes the construction date, steel liner material, and nominal wall thicknesses for each of the SST designs. A one-inch thick layer of cement mortar reinforced with 2x2-in. wire mesh fabric over 3-ply asphaltic membrane waterproofing is provided between steel liner and concrete wall of all SSTs except SX, A, and AX tanks. The 100-Series steel liners are circumferentially stiffened by 5 x 3-1/2 x 5/16-inch angle rings welded to the inner surface of the vertical cylindrical portion of the liner and are equally spaced at 4 ft 6 in. intervals. Figure 2 shows a schematic of the 100-Series steel liner for B, C, T, and U tank farms. The 200-Series steel liner has only one stiffener ring located at the top of the liner. A lead flashing seal is provided at the top stiffener ring of all the SST liners to prevent waste condensate from running down between the liner and the concrete wall. The 100-Series steel liner bottom is a shallow inverted spherical shell cap with 570-ft radius over a one-foot vertical rise from bottom center to tangent with knuckle (except SX which has 1 ft 2-7/8 in. rise and A and AX tanks which have flat bottoms). Similarly, the 200-Series steel liner bottom is a shallow inverted spherical shell cap with 55-ft radius over a six-inch vertical rise from bottom center to tangent with knuckle. The bottom liners rest on a 2-inch thick grout layer, a 3-ply asphaltic membrane waterproofing layer, and reinforced concrete foundation, which is supported by the soil; except AX tanks, where the bottom portion of the liner rest directly on the foundation slab. The AX concrete foundation slab contains radial drain slots under the steel liner for leak detection.

Buckling or uplift of the bottom region of the steel liners has occurred in the past for some SSTs in SX, A, and AX tank farms. These tank farms contained stored waste that self boiled. Bulging of the tank bottom liners was generally attributed to steam formation under the bottom liner during self-boiling operations (Barnes and Hanson 1958, Brownell 1958, and Beard and Hatch 1967). The steam resulted from vaporization of moisture contained either within the concrete foundation or free liquid trapped beneath the liner from a waste leak. Tank U-104 also bulged

about 5 feet in 1956 (General Electric 1956). This tank was sluiced for uranium recovery in 1955 and contained only sluicing water when it bulged. In addition, some A and AX tanks that have flat bottoms were found to have numerous ridges in the bottom plates, up to 6 inches high and 1 to 2 feet wide (RPP-5982, 2000). These plastically deformed ridges are attributed to construction residual bulges in the flat bottom liner that were subsequently compressed into narrow ridges due to the hydrostatic pressure from the waste loading and restrained thermal expansion of the tank bottoms by the surrounding concrete during the high-heat self-boiling operations. Although the current heat content of the SST stored waste has been greatly reduced due to natural radiation decay resulting in waste temperatures well below boiling; buckling or uplift of the steel liner during waste retrieval due to internal vacuum from ventilation system is still a concern.

Original design specification and drawings for most SSTs specify that liquid is to be stored at atmospheric pressure. Subsequent use of active ventilation on some tanks, such as 241-C-106 due to high-heat load, required that the vacuum not exceed the liquid level. Current OSD-T-151-00013 (2002) vacuum limits for active ventilated SSTs require the vacuum (in. water gauge) to be less than the stored waste height but not exceed 9 inches w.g. The lower vacuum limit is provided to prevent buckling (uplift) of the tank bottom when the waste level is low. The upper limit (9 in. w.g.) on the vacuum pressure guards against potential buckling of the liner cylindrical wall and excessive loading on the concrete dome of the tank.

If active ventilation is required during retrieval activities this limit is difficult to maintain as the waste level decreases and the tank approaches empty. In particular, because the bottoms of most SSTs are dished (except A and AX tanks) the depth of the waste varies radially from the center of the dished bottom. As the tank is emptied the outer portion of the dished bottom is uncovered while the center portion is still covered by waste. Hence, the OSD limits against buckling (uplift) of the bottom liner are reassessed herein in an effort to provide less restrictive constraints during retrieval operations, in particular as the tank approaches empty (bounding case). The corroded condition of the liners must be estimated for the time of retrieval to properly determine the allowable vacuum. Waste retrieval of all SSTs is scheduled for completion by September 2018, and closure of all SSTs is scheduled for completion by September 2024.

3.0 ASSUMPTIONS AND CONSIDERATIONS

Although buckling or uplift would likely be resisted by bonding forces of grout/mastic material between the liner and the surrounding concrete, the thermally aged condition of this bond may have been significantly reduced and hence cannot be relied upon. At the same time this lack of bond would likely allow the vacuum pressure on the inner surface of the liner to be equalized if the lead flashing seal at the top of the liner is not airtight, particularly along the vertical wall above the waste level. In any event, buckling of the vertical liner wall above the waste level during retrieval is of less concern because the buckled region is above the waste level and hence would not lead to waste leakage. Although buckling of the liner leads to high bending and membrane stresses these stresses may or may not result in a breach of the liner, particularly of the vertical wall above the waste level. However, buckling of the bottom liner is more

problematic to waste retrieval operations and could lead to leakage of remaining liquid or liquid used in sluicing retrieval operations.

The following is a summary of the assumptions and considerations in the analysis to determine the allowable vacuum for SSTs:

1. Dished bottom portion of steel liner is idealized as shallow spherical cap (except flat bottom A and AX tanks) under uniform net load due to internal vacuum in excess of self-weight of bottom liner and average waste level during retrieval. Bounding case is for empty tank.

2. Any bonding force between grout/mastic layer and steel liner is neglected.

3. Construction imperfections in the spherical shaped bottom liners are assumed bounded by results from open literature test data (see Section 8.0) and resulting bounding knockdown factors are applied.

4. Waste retrieval of all SSTs is scheduled for completion by September 2018, and closure of all SSTs is scheduled for completion by September 2024. However, to account for potential schedule delays for added conservatism and for simplicity the predicted accumulated corrosion loss for all liners is conservatively based on final retrieval by 2028. Reductions in liner thickness from uniform corrosion of the carbon steel liners is applied based on estimated accumulated corrosion given in the Appendix to the year 2002 and extrapolated to 2028. The rate of corrosion beyond the year 2002 is estimated in the Appendix to range from 0.1 to 0.2 mils/yr for the current benign condition of the waste.

5. A 10% reduction in elastic modulus and yield strength is applied based on estimated potential thermal aging effects (see Appendix).

6. Potential sidewall liner buckling is also addressed for completeness but is not considered likely. This assumes that any onset of buckling of the cylindrical wall liner will be prevented by pressure equalization between the inside and outside surfaces of the steel liner since the lead flashing at the top of the liner is not expected to be airtight. This also assumes that the vacuum is applied in a quasi-static (not dynamic) manner. Even if the sidewall liner did buckle, it is of less concern during retrieval because it would not likely lead to leakage of the remaining waste. Local buckling would occur between the circumferential stiffeners above the waste level. The post-buckled deformation would be self-limiting because it would likely lead to air leakage between the tank storage space and the liner-concrete interface, thus equalizing the pressure on the liner sidewall.

7. All potential buckling of the steel liner is considered as "local buckling" because the liner is not a load bearing structural component, all loads are resisted by the concrete structure by design. The liner provides the primary leak barrier. ASME Code Case N-284-1 (ASME, 1998b) imposes a factor of safety of 2 against local buckling which does not lead to collapse of the load bearing structure. Although a smaller safety factor might be argued in this application, a safety factor of 2 is imposed herein on the net differential vacuum pressure against buckling.

4.0 METHOD OF ANALYSIS

Apply empirical buckling correlations available from open literature and ASME Code Case N-284-1 (ASME 1998b) for shallow spherical cap under uniform external differential pressure load to assess the allowable vacuum in excess of self-weight and residual waste to prevent buckling (uplift) of the steel liner bottom. As the cylindrical wall portion of the steel liner is also subject to the vacuum load, buckling of the liner sidewall is also evaluated although it is not considered controlling as discussed above.

5.0 CONCLUSIONS

Internal vacuum from active ventilation should not exceed net pressure from the weight of the bottom liner and hydrostatic pressure from contained waste or buckling vacuum pressure of steel liner sidewall. The amount of corrosion loss in the liner thickness is the primary variable of interest as the tank approaches empty. Estimates for the general corrosion of the bottom and sidewall steel liner for SSTs are given in the Appendix and are extrapolated to 2028. The additional vacuum in excess of the self-weight and residual waste to cause buckling of the bottom liner is small for the 100-Series tanks (particularly as the wall thickness decreases due to corrosion) but is significant for the 200-Series tanks. That is, the allowable vacuum to prevent buckling or uplift of 100-Series SST liners is essentially controlled by the self-weight of the bottom liner and the residual waste level in the tank. However, in the case of the 200-Series SSTs, an additional vacuum is required in excess of the self-weight of the bottom liner and the residual waste level to cause buckling or uplift of the liner bottom as shown in Table 2.

The allowable tank vacuum is given in Table 2 for the SSTs in each of the tank farms based on the estimated range of general corrosion and average height of remaining waste from zero to four inches as tank is emptied during waste retrieval operations. Current OSD-T-151-00013 (2002) vacuum limits for active ventilated SSTs require the vacuum (inches water gauge) to be less than the stored waste height (lower limit) but not exceed 9 inches w.g. (upper limit). Table 2 provides a basis for increasing the current OSD lower vacuum limit as the tank approaches empty during waste retrieval operations provided that sidewall buckling can be precluded or discounted. The results in Table 2 for the 100-Series tanks generally support an allowable vacuum of 1.32 in. w.g. or greater when tank is empty; except for the 100-Series C and U tank farms which are limited to 0.86 in. w.g. for the predicted minimum wall thickness due to corrosion. Note that a tank specific analysis for the 100-Series tank 241-C-104 reported in RPP-11787 (2002) gave an allowable vacuum of 1.36 in. w.g. for an empty tank based on a retrieval date of 2008. In addition, in the tank specific analysis for the 100-Series tank 241-C-106 reported in RPP-8551 (2001) the allowable vacuum was given as 0.75 in. w.g. when tank is empty. For empty 200-Series tanks an allowable vacuum of 5.39 in. w.g. is supported by results given in Table 2.

In general, the buckling of the steel liner due to internal vacuum is elastic and is controlled by the buckling strength of the bottom portion of the liner when the tank is empty provided that the general corrosion of the sidewall is not significantly greater than that of the bottom portion of the liner. However, this is not always the case if the predicted high corrosion loss for the sidewall of some tanks is realized. If buckling of the sidewall liner cannot be precluded or discounted by air

leakage between tank storage space and liner-to-concrete interface then the allowable vacuum may be limited by the buckling of the sidewall depending on the extent of actual sidewall corrosion and residual waste level as shown in Table 2. The effect of sidewall buckling is discussed below.

Buckling of the sidewall liner is very sensitive to the sidewall corroded thickness and any potential air leak paths to the region between the liner and the surrounding concrete. Air leakage between the tank storage space and the liner-concrete interface under static pressure conditions would tend to equalize the pressure on the liner sidewall and prevent it from buckling. The minimum allowable vacuum for the liner sidewall is for the upper portion of the liner above the waste level due to the higher predicted corrosion in this region. Even if the sidewall did buckle it is of less concern during retrieval because it would not likely lead to leakage of the remaining waste. Local buckling would occur between the circumferential stiffeners above the waste level. The post-buckled deformation would be self-limiting because it would likely lead to air leakage between the tank storage space and the liner-concrete interface, thus equalizing the pressure on the sidewall. Although the lead flashing at the top of the liner is provided to prevent condensate from running down between the liner and the concrete wall, it does not provide an airtight seal. Some liner walls have through-wall holes due to pitting corrosion as evidenced by tar drip lines on the inner surface of the liner. Air leakage between the waste storage space and the bottom liner interface to the concrete foundation cannot be assured because the weight of the liner sidewall would tend to seal the bottom region of the liner from the waste storage air space.

Buckling of the bottom portion of the steel liner does not necessarily result in a liner breach. Previous analysis (McCall 1994) has shown that the bottom of the steel liner is extremely flexible. Because of this flexibility the calculation of the post-buckled displacement and tensile stresses in the bottom liner due to vacuum in excess of the buckling vacuum pressure requires a large displacement analysis. A simplified large displacement analysis is provided in RPP-11787 (2002) assuming that the bottom liner can be modeled as a uniformly loaded, thin circular flat plate, clamped at the outer edge. Applying the large displacement analysis given in Timoshenko et al. (1959) for the idealized plate model, the vacuum pressure to cause initial membrane (through thickness) yielding is approximately 49 in. w.g. for the predicted minimum bottom liner thickness of 0.168 inches for tank 241-C-104 when tank is empty per RPP-11787 (2002). The post-buckled center displacement of the bottom liner idealized as a flat plat is approximately 14 inches for initial membrane yielding at center of bottom liner. For the dished bottom liner an additional 24 inches (twice the rise of the shallow spherical shell) should be added to account for the displacement associated with the snap through of the shallow spherical cap. Although the vacuum pressure to cause initial membrane yielding at the center of the bottom liner is greatly in excess of the expected operating vacuum pressure of 1 to 6 in. w.g., a breach of the bottom liner cannot be ruled out due to potential local pitting corrosion of the liner, independent of the magnitude of the vacuum.

6.0 LINER MATERIAL PROPERTIES AND WALL THICKNESS

6.1 LINER MATERIAL PROPERTIES

Materials of construction for the SST steel liners are identified in Table 1 including specified minimum yield strength at room temperature. However, because of the large radius-to-thickness ratios for the liner the liner buckling of the bottom or sidewall is elastic. A 10% reduction in elastic modulus was applied to conservatively account for potential thermal aging effects as discussed in the Appendix. Hence, the elastic modulus at 100 °F (assumed temperature at retrieval) for the carbon steel liner becomes

$$E = 26.4 \times 10^6 \text{ psi.} \tag{1}$$

Poisson's ratio is taken as

$$\nu = 0.3 \tag{2}$$

The unit weight of the carbon steel liner is

$$\gamma = 490 \text{ lbf/ft}^3 = 0.284 \text{ lbf/in}^3. \tag{3}$$

The self-weight pressure from of liner bottom is given by

$$p_w = \gamma h \qquad \text{where } h = \text{liner thickness.} \tag{4}$$

6.2 LINER WALL THICKNESS

Nominal liner thicknesses (bottom and sidewall) for the SST steel liners are identified in Table 1 for each tank farm. The mill tolerance is given from ASTM A20 as -10 mils / +30 mils. A conservative analysis of potential thickness reduction of the bottom and sidewall steel liner due to general (uniform) corrosion is given in the Appendix. The estimated range of corrosion induced thickness loss from initial construction to year 2002 is given in Table 2 of the Appendix. The estimated min/max corrosion rate beyond the year 2002 for current benign waste condition of the stored waste is given in the Appendix as:

$$r_{min} = 0.1 \text{ mils/yr} = 0.0001 \text{ inches/yr} \tag{5a}$$
$$r_{max} = 0.2 \text{ mils/yr.} \tag{5b}$$

Hence, the min/max liner thickness extrapolated to 2028 is given by

$$h_{min} = h_{nom} - 10 \text{ mils} - h_{max\ corrosion\ loss} - r_{max}(2028 - 2002) \tag{6a}$$
$$h_{max} = h_{nom} + 30 \text{ mils} - h_{min\ corrosion\ loss} - r_{min}(2028 - 2002) \tag{6b}$$

where

$h_{min\ corrosion\ loss}$ = minimum corrosion loss from Table 2 of the Appendix

$h_{max\ corrosion\ loss}$ = maximum corrosion loss from Table 2 of the Appendix.

The resulting predicted maximum/minimum thickness values for the bottom and sidewall portions of the steel liner are given in Table 2 herein for each tank farm.

7.0 WASTE PROPERTIES

The waste currently in the SSTs varies in depth and specific gravity (SpG) from tank to tank. Most SSTs have been interim stabilized removing much of the pumpable liquid. However, retrieval techniques, such as sluicing, will likely introduce additional liquid. Hence, the average SpG of the waste will approach that of water as the waste level decreases and the tank approaches empty. For comparison a SpG of 1.25 and 1 (water) are considered in the analysis as the waste level approaches empty.

The unit weight of water is taken as

$$\gamma_{water} = 62.4\ \text{lbf/ft}^3 = 0.0361\ \text{lbf/in}^3. \tag{7}$$

The pressure on the bottom of liner from waste of specific gravity = SpG and average depth = h_{waste} is given by

$$p_{waste} = SpG\ \gamma_{water}\ h_{waste} \tag{8}$$

The waste induced pressure approaches zero as the tank approaches empty.

8.0 ALLOWABLE VACUUM ANALYSIS

As the SSTs are emptied during waste retrieval operations, compressive membrane stresses in the steel liner bottom could cause the bottom liner to buckle. The sources for the compressive induced stresses include internal vacuum from active ventilation, restrained radial differential thermal expansion of the bottom liner relative to the concrete outer wall, and residual weld induced stresses (construction welds were not stress relieved). However, as the tank waste level is reduced during waste retrieval the heat load is also reduced. Hence, differential thermal expansion induced compressive stresses in the tank bottom are reduced and should not be a significant consideration as the tank approaches empty. However, residual stresses and construction geometric distortions can significantly reduce the buckling strength. Due to local heating during welding, complex thermal stresses occur during welding; and residual stress and distortion result after welding. High tensile residual stresses in areas near the weld may cause stress corrosion cracking under certain conditions; distortion and compressive residual stress in the base metal plate may reduce the buckling strength of the structural component. Weld induced distortions are particularly detrimental for structures that are imperfection sensitive such as the shallow spherical cap that forms the steel liner bottom of most SSTs. Figure 3 shows potential distortions in the bottom liner during construction (BX Farm tank with 3/8-inch bottom

plate thickness). Note the puddle areas of standing water that clearly indicate distortions in the tank bottom on the order of the tank thickness or greater.

8.1 TANK BOTTOM BUCKLING/UPLIFT

The dished tank bottom is modeled as an inverted shallow spherical shell of radius, R_S, thickness, t (symbolically given by the notation, h, herein), with rise, H_S, over cord length, c_S, within included angle, $2\phi_S$, and under net uniform external pressure, p (see Figure 4). For the A and AX flat bottom tanks, no additional resistance to initial bottom uplift other than self weight and hydrostatic pressure of waste is considered. The relations between c_s, R_s, and ϕ_s for the dished bottom liners are given through simple geometry (see Figure 4) by

$$R_s = \frac{1}{2}\left[H_s + \frac{c_s^{\,2}}{4H_s}\right] \tag{9}$$

$$\phi_s = \operatorname{asin}\left(\frac{c_s}{2R_s}\right). \tag{10}$$

The cord length can be calculated from Equation 9 if R_s and H_s are given or from Equation 10 if R_s and ϕ_s are given.

8.1.1 Buckling Correlation for Shallow Spherical Cap

The classical buckling pressure for a "perfect" shallow spherical cap under uniform external pressure is given by classical buckling pressure for complete spherical shell (Baker et al. 1972) as:

$$p_{cl} = \frac{2}{C}E\left(\frac{h}{R_s}\right)^2 \tag{11a}$$

where

$$C = \sqrt{3\left(1-\nu^2\right)} \tag{11b}$$

E and ν are the elastic modulus and Poisson's ratio, respectively as given by Equations 1 and 2 above. R_s is given by Equation 9 and "h" is the liner thickness.

Zoelly first developed the classical buckling pressure for complete spherical shell in 1915 (Baker et al. 1972). However, the actual buckling pressure is typically much lower than the results given by Equation 11a due to initial imperfections.

8.1.1.1 Effect of Imperfections. Early experimental results for clamped spherical caps under external pressure are shown in Figure 5 from Bushnell (1985) for critical buckling pressure to classical buckling pressure ratio (p_{cr}/p_{cl}) versus shallowness parameter (λ) given by

$$\lambda = \sqrt[4]{12\left(1-\nu^2\right)}\sqrt{\frac{R_s}{h}}\,2\sin\left(\frac{\phi_s}{2}\right) = 2\sqrt{C\frac{H_s}{h}} \tag{12}$$

where H_s is the rise of the apex of the spherical cap as shown in Figure 4, C is defined by Equation 11b. R_s and ϕ_S is given by Equation 9 and 10, respectively and h is the wall thickness.

The effects of weld induced residual stress and distortion as well as variations in boundary conditions and load are assumed to be contributors to the observed reductions in buckling strength. It has generally been accepted that initial imperfections of the test specimens was the principal cause for the wide scatter in experimental data shown in Figure 5. The initial imperfection can be from shape, thickness, boundary conditions, or loads. Each of these quantities has a different effect on the maximum load-carring capacity of the shell. For spherical shells under external pressure, it is well known that the shell is highly imperfection-sensitive to unstable compound (two or more modes) branching (Citerley 1982). An expansion of the governing nonlinear equilibrium equations in terms of potential symmetric and asymmetric buckling modes leads to the following relations (Hutchinson 1967 and Bushnell 1985) for $\alpha = p_{cr}/p_{cl}$ and $\xi = w_o/h$ (normalized imperfection shape amplitude):

2-mode case (symmetric), $\xi_1 > 0,\ \xi_2 = 0$

$$\left(1-\alpha_1\right)^2 = \frac{9C}{8}\xi_1\alpha_1 \Rightarrow \alpha_1 = 1+\frac{9}{16}C\xi_1 - \frac{3}{16}\sqrt{32C\xi_1 + 9C^2\xi_1^2} \tag{13a}$$

2-mode case (asymmetric), $\xi_1 = 0,\ \xi_2 \neq 0$

$$\left(1-\alpha_2\right)^2 = \frac{27\sqrt{3}\,C}{32}\left|\xi_2\right|\alpha_2 \Rightarrow \alpha_1 = 1+\frac{27}{64}\sqrt{3}\,C\left|\xi_2\right| - \frac{3}{64}\sqrt{384\sqrt{3}\,C\left|\xi_2\right| + 243C^2\xi_2^2} \tag{13b}$$

3-mode case

$$\left(1-\alpha_3\right)^2 = \frac{9C}{16}\xi_3\alpha_3 \Rightarrow \alpha_3 = 1+\frac{9}{32}C\xi_3 - \frac{3}{32}\sqrt{64C\xi_3 + 9C^2\xi_3^2} \tag{13c}$$

Equations 13a, b and c are plotted in Figure 6. Although the results shown in Figure 6 are strictly valid for $\xi << 1$ due to the numerical expansion technique applied in the solution, the results do indicate the effect of initial shape imperfections on reducing the classical buckling load of the spherical shell cap under external uniform pressure. These results are not used here directly but help to explain the experimentally observed reductions in buckling pressure shown in Figure 5.

8.1.1.2 Effect of Residual Stress. The fabrication process of forming and welding create residual stresses. Residual compressive stresses can reduce the buckling strength of a structure. Residual stresses are difficult to measure but have been correlated with experimental collapse pressure. Elaborate analytical modeling simulations of the welding process to quantitatively predict the effect on buckling have been relatively unsuccessful or impractical. Experimental studies of cylindrical and spherical shells with welded seams have shown that the residual compressive stresses created by the welding process reduce the critical buckling stress less than 5 percent. Whereas, the associated distortion (weld shrink, etc.) create an imperfection that is more significant in reducing the collapse pressure (Harvey 1991).

The SST liners were not stress relieved. However, the liner bottoms have been exposed to high temperatures over an extended period. In the case of Tank 241-C-106, the bottom liner was exposed to approximately 300 ^{o}F for approximately 10 years (WHC-SD-W320-ANAL-001). Although this combination of time at temperature may cause some reduction in the residual stress, the analysis given in the Appendix concluded that any reduction in residual stresses would be insignificant. For analysis purposes any effect of residual stress on reducing the buckling pressure is assumed to be accounted for in experimentally derived "knockdown" factors applied to theoretical buckling pressure.

8.1.1.3 Spherical Shell Buckling Knockdown Factor. The following "knockdown" factor is given by Baker et al. (1972) as a lower bound to the experimental results given in Figure 5 for clamped spherical shells

$$p_{cr}/p_{cl} = \alpha(\lambda) = 0.14 + \frac{3.2}{\lambda^2} \quad \text{for } \lambda > 2 \tag{14}$$

where λ is the shallowness parameter defined by Equation 12. Equation 14 is plotted in Figure 7 for comparison to experimental data in Figure 5.

8.1.1.4 Allowable Vacuum Against Tank Bottom Buckling/Uplift. The resulting allowable vacuum pressure accounting for self-weight of liner bottom (Equation 4), average pressure from waste (Equation 8), and corresponding critical buckling stress (Equation 14) is given as

$$p_{allowable}^{bottom} = \frac{\alpha(\lambda)}{FS} p_{cl}(R_s, h, E) + p_w(h) + p_{waste}(h_{waste}, SpG) \tag{15a}$$

or using Equation 11a, the above becomes

$$p_{allowable}^{bottom} = \frac{\alpha(\lambda)}{FS} \frac{2}{C} E \left(\frac{h}{R_s}\right)^2 + p_w(h) + p_{waste}(h_{waste}, SpG) \tag{15b}$$

where α is given by Equation 14 as a function of λ given by Equation 12 and p_{cl}, p_w, and p_{waste} are given by Equations 11, 4 and 8, respectively. FS is the factor of safety against buckling on the net vacuum pressure in excess of self-weight of liner bottom and average waste pressure at liner bottom.

All potential buckling of the steel liner is considered as "local buckling" because the liner is not a load bearing structural component, all loads are resisted by the concrete structure by design. The liner provides the primary leak barrier. ASME Code Case N-284-1 (ASME, 1998b) imposes a factor of safety of 2 against local buckling which does not lead to collapse of the load bearing structure. Although a smaller safety factor might be argued in this application, a safety factor of two (2) is imposed herein on the net differential vacuum pressure against buckling.

8.2 ASME CODE APPROACH (Alternate Calculation)

According to HW-1946 (1943), *Specification for Composite Storage Tanks - Bldg. #241 at Hanford Engineer Works, Project 9536*, the steel liners for the B, C, T, and U Tank Farms were designed, fabricated, and erected in accordance with the then current *Standard Specifications for Elevated Steel Water Tanks, Standpipes, and Reservoirs* as promulgated by the American Waterworks Association in conjunction with The American Welding Society where applicable and not at variance with any portion of the HW-1946 specification. Although the steel liners were not designed to the ASME, Section III, Division 1, requirements for the design of metal containment shell structures, the ASME (1998b) Code Case N-284-1, *Metal Containment Shell Buckling Design Method, Class MC, Section III, Division 1*, provides an acceptable method for determining the buckling capacity of shells that are fabricated from metal plates where the plates are cold or hot formed and joined by welding.

The stability criteria is based upon classical linear bifurcation analysis which has been reduced by capacity reduction factors which account for the effects of imperfections and non linearity in geometry and boundary conditions and by plasticity reduction factors which account for non linearity in material properties. The reduction factors are determined from lower-bound buckling values from available test data.

Although the rules from Case N-284-1 are <u>strictly valid</u> for shells with <u>radius-to-thickness ratios up to 1000</u>, shell thickness of 1/4 inch or greater, and built to fabrication requirements of ASME NE-4222, the code equations are applied herein as an alternate calculation method for buckling of the shallow spherical shell bottom liner and as a direct calculation for the buckling of the cylindrical shell sidewall of the liner.

For the bottom liner, because of the large R_s/h ratio (for nominal wall thickness of 0.25 inches, R_s/h = 6,840 in./0.25 in. = 27,360) the critical buckling stress is elastic. Similarly, for the cylindrical wall of liner (for nominal wall thickness of 0.25 inches, R_{cyl}/h = 450 in./0.25 in. = 1,800) the critical buckling stress is elastic.

8.2.1 Shallow Spherical Shell Cap

Capacity Reduction Factor
(equal biaxial compression)

$$\alpha_{2L} = \begin{cases} 0.627 & \text{if } M < 1.5 \\ 0.837 - 0.14M & \text{if } 1.5 \le M < 1.73 \\ \dfrac{0.826}{M^{0.6}} & \text{if } 1.73 \le M < 23.6 \\ 0.124 & \text{otherwise} \end{cases} \tag{16a}$$

where

$$\mathrm{M} = \frac{\mathrm{R_s}\, 2\phi_s}{\sqrt{\mathrm{R_s\, h}}} \tag{16b}$$

Theoretical Elastic Instability Stress
(equal biaxial compression)

$$\sigma_{cL} = \mathrm{C'E}\frac{\mathrm{h}}{\mathrm{R_s}} \tag{17a}$$

where

$$C' = \begin{cases} 0.630 & \text{if } M < 1.5 \\ \dfrac{0.904}{M^2} + 0.1013M^2 & \text{if } 1.5 \le M < 1.73 \\ 0.605 & \text{otherwise} \end{cases} \tag{17b}$$

The resulting allowable vacuum for the bottom liner by the ASME method is given by

$$^{\mathrm{ASME}}\mathrm{p}^{\mathrm{bottom}}_{\mathrm{allowable}} = \frac{2\alpha_{2L}(M)}{FS}\sigma_{cL}\frac{h}{R_s} + \mathrm{p_w}(\mathrm{h}) + \mathrm{p_{waste}}(\mathrm{h_{waste}}, \mathrm{SpG}) \tag{18a}$$

or

$$^{\mathrm{ASME}}\mathrm{p}^{\mathrm{bottom}}_{\mathrm{allowable}} = \frac{2\alpha_{2L}(M)C'(M)}{FS}E\left(\frac{h}{R_s}\right)^2 + \mathrm{p_w}(\mathrm{h}) + \mathrm{p_{waste}}(\mathrm{h_{waste}}, \mathrm{SpG}) \tag{18b}$$

For equivalence between Equations 18b and 15b

$$2\alpha_{2L}(M)C'(M) \approx \alpha(\lambda)\frac{2}{\mathrm{C}} \tag{19}$$

For R_s = 570 ft = 6,840 in., H_s = 1 ft = 12 in., h = 0.25 in., c_s = 67.48 ft = 810 in. and ν =0.3 gives ϕ_S = 3.4 degrees ≈ 0.059 radians, C = 1.652, λ = 17.81, $\alpha(\lambda)$ = 0.15, M = 19.63, α_{2L} = 0.138, and C` = 0.605, so

$$2\alpha_{2L}(M)C'(M) = 0.167 \approx \alpha(\lambda)\frac{2}{C} = 0.182$$

Hence, Equations 15 and 18 give similar results within 10% of each other.

8.2.2 Buckling Check for Cylindrical Wall of Steel Liner per ASME Code Case N-284-1

Applying the ASME method to the cylindrical sidewall of the liner between circumferential stiffeners gives the following.

Capacity Reduction Factor

$$\alpha_{\theta L} = 0.8 \tag{20}$$

Theoretical Elastic Instability Stress
(hoop compression, no end pressure, $\sigma_\phi(p) = 0$)

$$\sigma_{\theta reL} = C_{\theta r} E \frac{h}{R_{cyl}} \tag{21a}$$

where

$$C_{\theta r} = \begin{cases} 1.616 & if\ M_\phi \le 1.5 \\ \dfrac{2.41}{M_\phi^{1.49} - 0.338} & if\ 1.5 < M_\phi < 3.0 \\ \dfrac{0.92}{M_\phi - 1.17} & if\ 3.0 \le M_\phi < 1.65\dfrac{R_{cyl}}{h} \\ 0.275\dfrac{h}{R_{cyl}} + \dfrac{2.1}{M_\phi^4}\left(\dfrac{R_{cyl}}{h}\right)^3 & otherwise \end{cases} \tag{21b}$$

and

$$M_\phi = \frac{L_\phi}{\sqrt{R_{cyl}\, h}} \tag{21c}$$

R_{cyl} and h are the radius and wall thickness of the liner sidewall and L_ϕ is the length between circumferential stiffeners.

The resulting allowable vacuum for the liner sidewall by the ASME method is given by

$$^{ASME}p^{sidewall}_{allowable} = \frac{\alpha_{\theta L}}{FS}\sigma_{\theta reL}\frac{h}{R_{cyl}} = \frac{\alpha_{\theta L}}{FS} C_{\theta r} E \left(\frac{h}{R_{cyl}}\right)^2 \tag{22}$$

Alternate Calculation for Buckling Cylindrical Wall of Steel Liner

Per Young, 1989, "Roark's Formulas for Stress and Strain," Table 35-19b

$$ {}^{\text{Roark}}p_{\text{allowable}}^{\text{sidewall}} = \frac{0.807}{FS}\frac{\mathrm{E}h^2}{\mathrm{L}_\phi R_{cyl}}\left[\left(\frac{1}{1-\nu^2}\right)^3 \frac{h^2}{R_{cyl}^2}\right]^{\frac{1}{4}} \tag{23} $$

For R_{cyl} = 37.5 ft = 450 in., h = 0.25 in., L_ϕ = 4.5 ft = 54 in. and E = 26.4 x 10^6 psi, ν =0.3, and FS = 2 gives M_ϕ = 5.09, $C_{\theta r}$ = 0.235, so

$$ {}^{\text{ASME}}p_{\text{allowable}}^{\text{sidewall}} = 21.2\,in.w.g. \approx {}^{\text{Roark}}p_{\text{allowable}}^{\text{sidewall}} = 19.2\,in.w.g. $$

Hence, the results from Equations 22 and 23 are within 10% of each other.

9.0 RESULTS

The allowable vacuum for the bottom liner and sidewall are given in Table 2 for each of the tank farms by application of Equations 15 and 22, respectively for the min/max range of corrosion wall thickness loss given in Table 2 of the Appendix extrapolated to 2028. For the bottom liner the allowable vacuum is given for an empty tank and for an average waste height of 1, 2, 3, and 4 inches with a waste SpG of 1 and 1.25. For the sidewall the allowable vacuum is given for the lower and upper region of the vertical cylindrical wall portion of the liner. The amount of corrosion loss in the liner thickness is the primary variable of interest as the tank approaches empty. The pressure to over come the self-weight of the bottom liner and remaining waste mainly controls the allowable vacuum. The additional vacuum in excess of the self-weight and residual waste to cause buckling of the bottom liner is small for the 100-Series tanks (particularly as the wall thickness decreases due to corrosion) but is significant for the 200-Series tanks. That is, the allowable vacuum to prevent buckling or uplift of 100-Series SST liners is essentially controlled by the self-weight of the bottom liner and the residual waste level in the tank. However, in the case of the 200-Series SSTs, an additional vacuum is required in excess of the self-weight of the bottom liner and the residual waste level to cause buckling or uplift of the liner bottom as shown in Table 2.

In general, the buckling of the steel liner due to internal vacuum is elastic and is controlled by the buckling strength of the bottom portion of the liner when the tank is empty provided that the general corrosion of the sidewall is not significantly greater than that of the bottom portion of the liner. However, this is not always the case if the predicted high corrosion loss for the sidewall of some tanks is realized. The effect of sidewall buckling is discussed below.

Buckling of the sidewall liner is very sensitive to the sidewall corroded thickness and any potential air leak paths to the region between the liner and the surrounding concrete. Air leakage between the tank storage space and the liner-concrete interface under quasi-static pressure conditions would tend to equalize the pressure on the liner sidewall and prevent it from buckling.

Even if the sidewall did buckle it is of less concern during retrieval because it would not likely lead to leakage of the remaining waste. Local buckling would occur between the circumferential stiffeners above the waste level. The post-buckled deformation would be self-limiting because it would likely lead to air leakage between the tank storage space and the liner-concrete interface, thus equalizing the pressure on the sidewall. Although the lead flashing at the top of the liner is provided to prevent condensate from running down between the liner and the concrete wall, it does not provide an airtight seal. Air leakage between the waste storage space and the bottom liner interface to the concrete foundation cannot be assured because the weight of the sidewall would tend to seal the bottom region of the liner from the waste storage air space. Hence, liner sidewall buckling is not considered likely or controlling and is provided for information only as indicated in Table 2.

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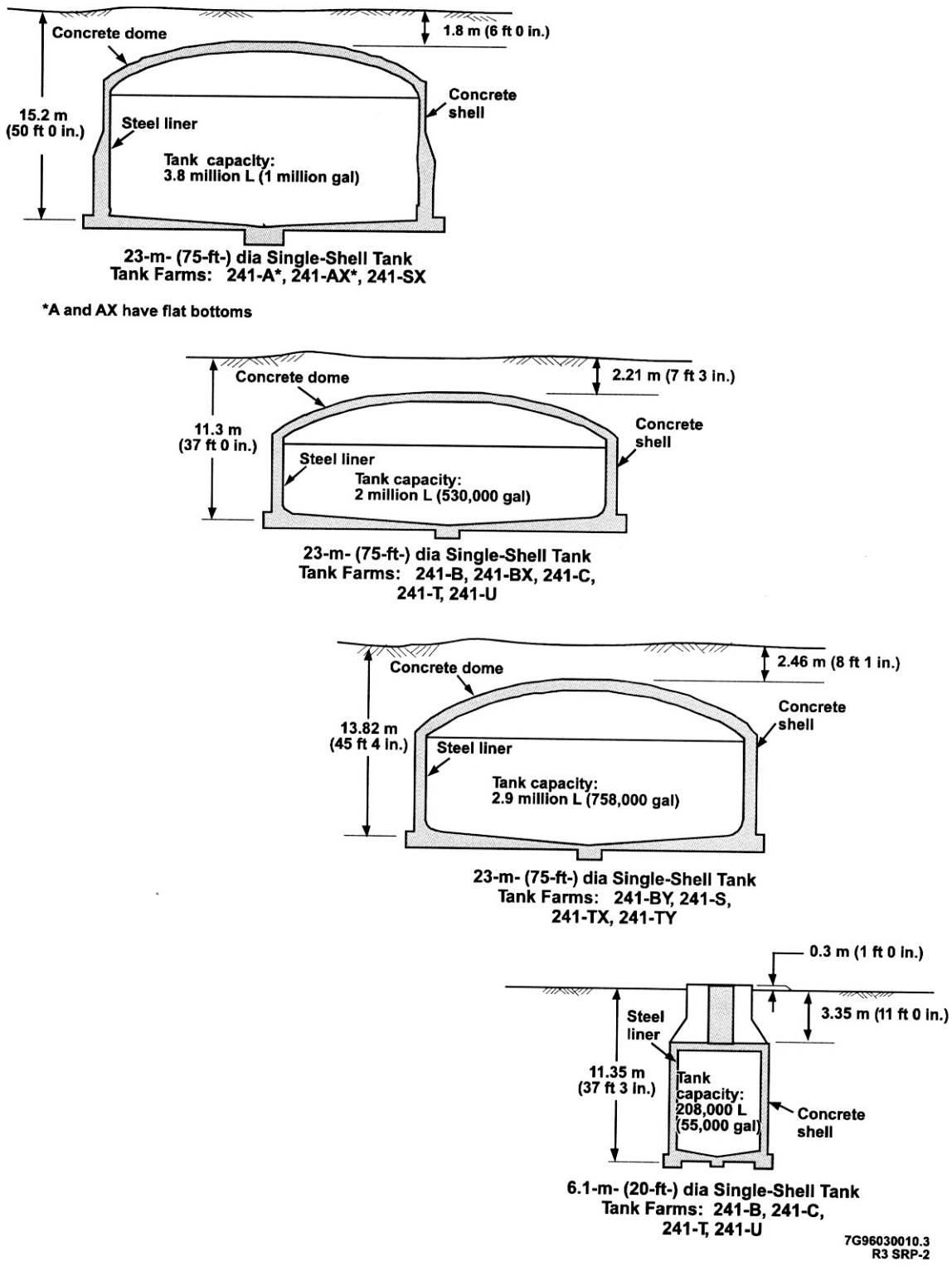
Figure 1. 100- and 200-Series Single-Shell Tank Configurations.



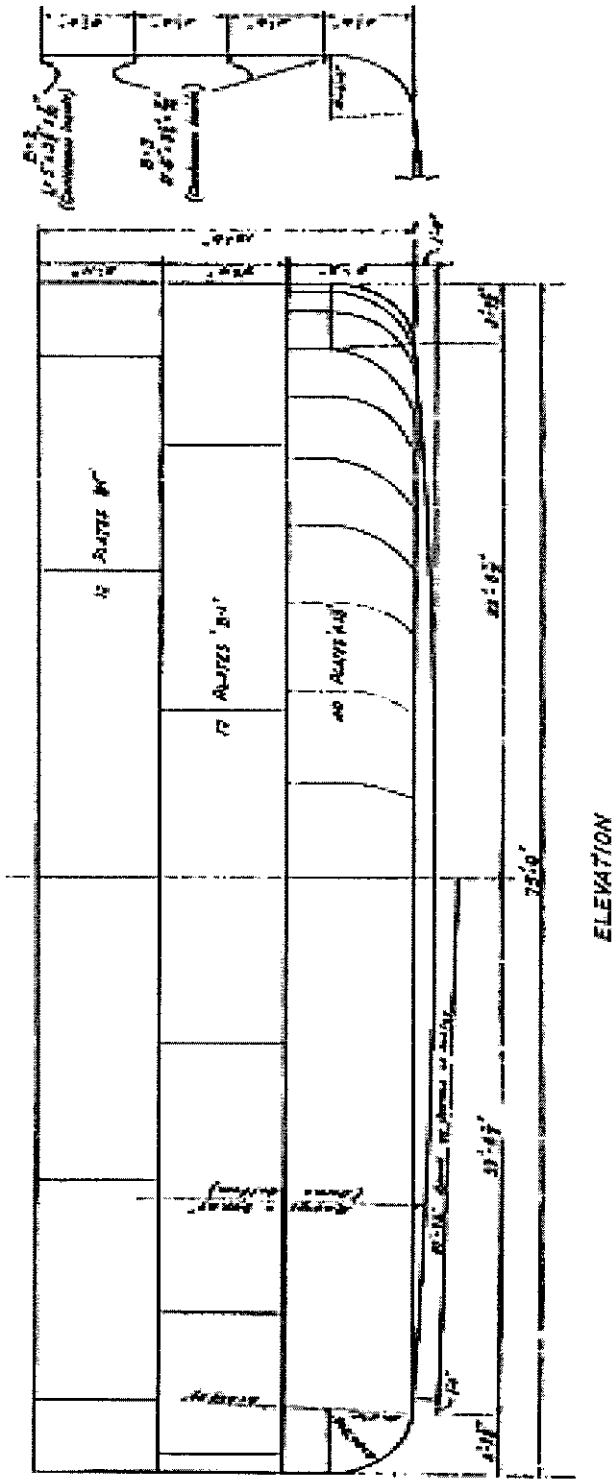


Figure 2. Steel Liner for 100-Series B, C, T, and U Tank Farms. (Drawing D-3)

Figure 3. Typical Construction Geometric Imperfections in Single-Shell Tank Steel Liner Tank Bottom. (241-BX Tank Farm, 1309-Negative 1947)

Figure 4. Geometry of Spherical Cap Under Uniform External Pressure. (Baker et al. 1972)

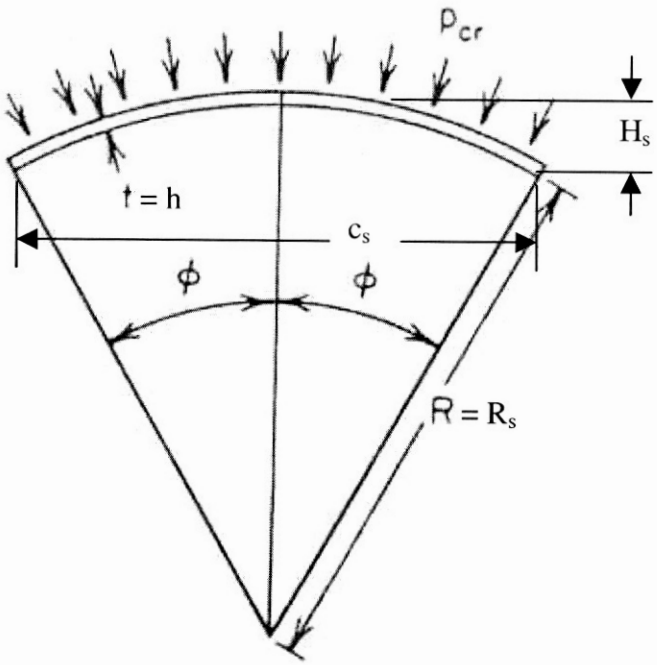


Figure 5. Experimental Results for Clamped Spherical Caps Under External Pressure Compared to Theory. (Figure 30, Bushnell 1985)

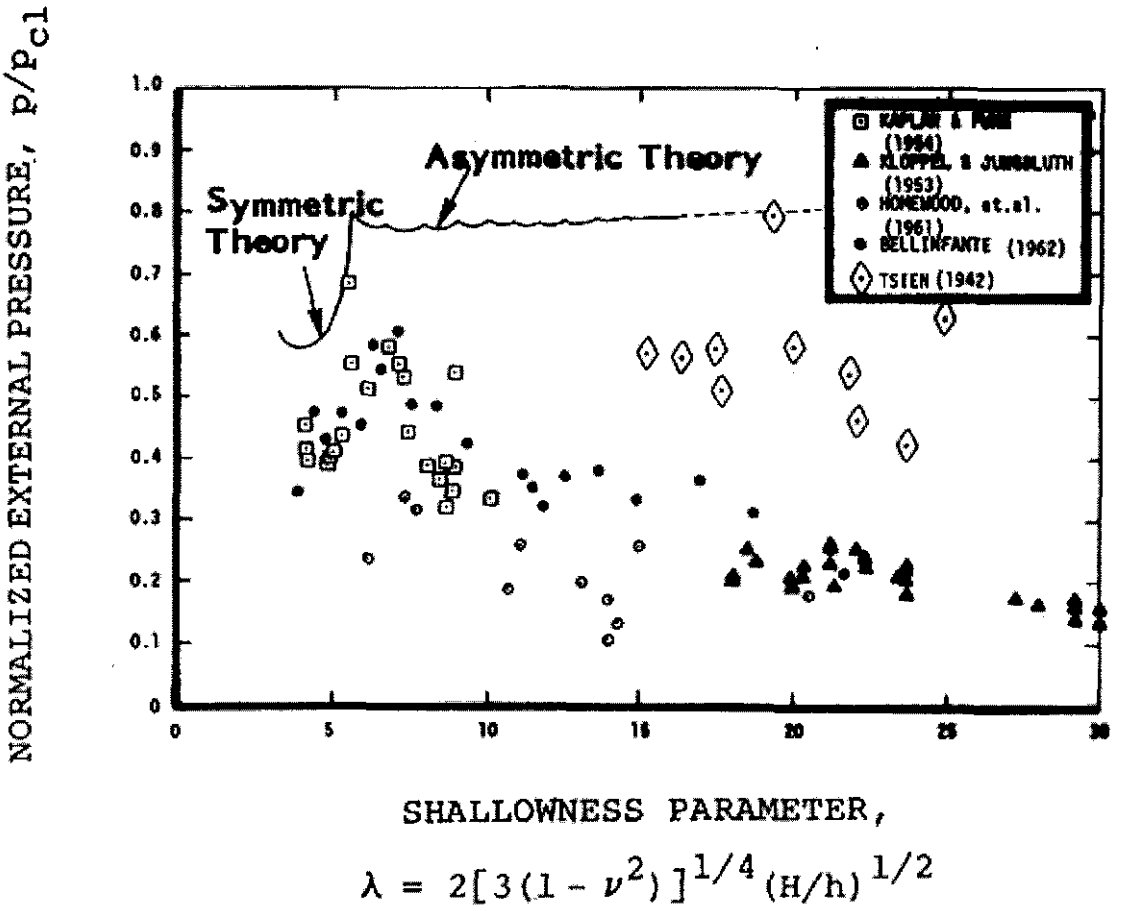


Figure 6. Effect of Shape Imperfection on Buckling of Spherical Shell under Uniform External Pressure.

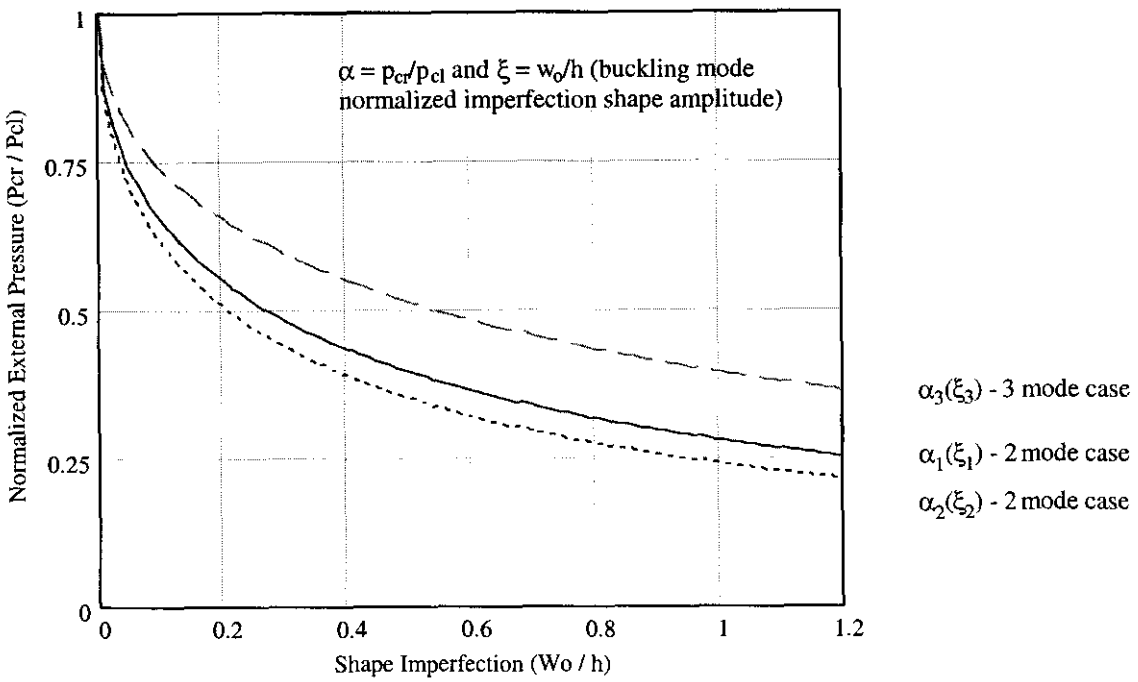


Figure 7. Recommended Design Buckling Pressure Ratio (p_{cr}/p_{cl}) for Spherical Caps Under Uniform External Loading. (Baker et al. 1972)

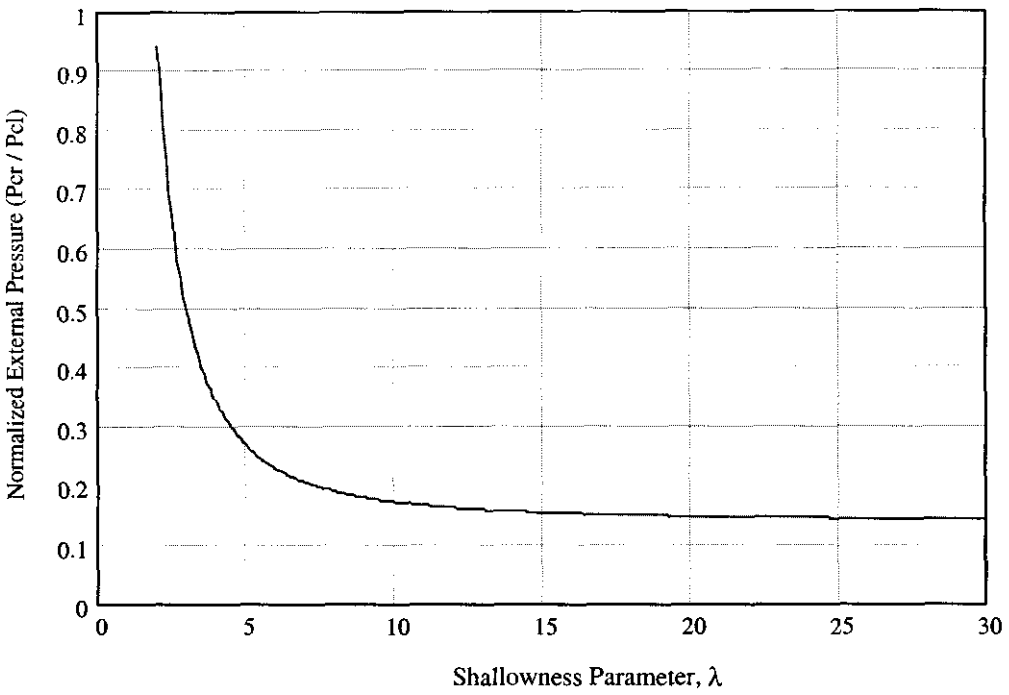


Table 1. Summary of Single-Shell Tank Steel Liner Design Parameters.

Tank Farm	Storage Volume (Kgal)	Constructed	Hanford Construction Specification	Steel Liner (no structural tie between concrete and steel liner and no post-weld stress relief)[1]								
				Steel Design Code	Tank Steel ASTM Spec. (Repl. ASTM) Yield Strength (ksi)	Wall Thickness (in.)					Weld Specification	
						Bottom	Bottom Knuckle	Vertical Wall		Key Ref. Drawing	Proc.	Qual.
100-Series (75-ft cylindrical inner diameter)												
B,C T,U	530	1943-44	HWS-1946	AWWA	A7-39 (A283, Gr. D) $F_Y = 33$	¼ (dished[2])	5/16 (4-ft radius)	1/4		W 71387	AWS	AWS
BX	530	1946-47	HWS-1946	AWWA	A7-39 (A283, Gr. D) $F_Y = 33$	3/8 (dished[2])	5/16 (4-ft radius)	1/4		H-2-602	AWS	AWS
TX	758	1947-48	HW-3061	AWWA	A285-46 Grade Unknown F_Y=24-30	3/8 (dished[2])	3/8 (4-ft radius)	5/16 (bot. 6 ft) ¼ (top 9 ft)		H-2-809	AWS	AWS
BY	758	1948-49	HW-3783	ASME Sect. VIII 1946	A283-46T or A285-46 Grade A,B, or C F_Y=24-30					H-2-1313	ASME Sect. VIII	ASME Sect. IX
S	758	1950-51	HW-3937	ASME Sect. VIII 1946	A283-46T Grade B F_Y=27				5	H-2-1784	ASME Sect. VIII	ASME Sect. IX
TY	758	1951-52	HW-4696 HW-4585	ASME Sect. VIII 1946	A283-49T Grade B F_Y=27					H-2-2245	ASME Sect. VIII	HW-4595 ASME Sect. IX
SX	1,000	1953-54	HW-4957	AWWA	A283-52T Grade A or B F_Y=24-27	3/8 (dished[3])	None (90°)	3/8		H-2-39511	HW-4925-S	HW-4900-S
A	1,000	1954-55	HWS-5614 HWS-4799-S	ASME Sect. VIII 1946	A283-52T or A285-52aT Grade B or C F_Y=27-30	3/8 (flat)				H-2-55911	HW-4924-S HW-4926-S	HW-4900-S
AX	1,000	1963-64	HWS-4798-S HWS-8237	ASME Sect. VIII 1962	A201-61T, Gr. A (A515 Gr. 55) $F_Y = 30$	3/8 (flat)	3/8 (4- to 8-in. radius)	3/8		H-2-44562	ASME Sect. VIII	ASME Sect. IX
200-Series (20-ft cylindrical inner diameter)												
B,C T,U	55	1943-44	HWS-1946	AWWA	A7-39 (A283, Gr. D) $F_Y = 33$	¼ (dished[4])	5/16 (4-ft radius)	1/4	6	HW-72742	AWS	AWS

ASME = American Society of Mechanical Engineers
ASTM = American Society for Testing and Materials
AWWA = American Water Works Association
AWS = American Welding Society
HW = Hanford Works
HWS = Hanford Works Specification

[1] One-inch thick layer of cement mortar reinforced with 2x2-in. wire mesh fabric over 3-ply asphaltic membrane waterproofing is provided between steel liner and concrete wall of all SSTs except 100-Series SX, A, and AX. Two-inch thick grout layer reinforced with 2x2-in. wire mesh fabric over 3/8-in. thick 3-ply asphaltic membrane waterproofing is provided between steel liner and concrete foundation of all SSTs except 100-Series AX which has drain slots provided in foundation under liner.

[2] Bottom is dished with 570-ft spherical radius over 1-ft rise from center of tank bottom to bottom-knuckle transition.

[3] Bottom is dished with 570-ft spherical radius over 1-ft 2 7/8-in. rise from center of tank bottom to transition with cylindrical wall.

[4] Bottom is dished with 55-ft spherical radius over ½-ft rise from center of tank bottom to bottom-knuckle transition.

[5] Circumferentially stiffened by welding of 5 x 3-1/2 x 5/16-in. angle rings (ASTM A7-39, replacement ASTM A36) to inner surface of liner vertical wall equally spaced at 4 1/2-ft intervals.

[6] Circumferentially stiffened by welding of 5 x 3-1/2 x 5/16-in. angle ring (ASTM A7-39, replacement ASTM A36) at top inner surface of liner vertical wall. Height of liner vertical wall from bottom liner to top stiffener ring is 22.5 ft.

Table 2. Allowable Vacuum for Single-Shell Tanks.

Tank Farm	Steel Liner Bottom Allowable Vacuum: Nominal wall thk (in.)	Corrosion loss at 2002 (min/max) (mils)	Bottom spherical cap: Radius R_s (in.)	Bottom spherical cap: Rise H_s (in.)	Wall thk at 2028 (max/min) (in.)	Buckling parameters: Classical buckling p_{cl} (in. w.g.)	Buckling parameters: Shallowness λ	Buckling parameters: Knockdown factor α	Self weight pressure p_w (in. w.g)	Waste SpG	Bottom allowable vacuum (in. w.g.) Average waste height, h_{waste} (in.): 0	1	2	3	4	Steel Liner Sidewall Allowable Vacucm (for information only): Wall location	Nominal wall thk (in.)	Corrosion loss at 2002 (min/max) (mils)	Cylinder radius R_{cyl} (in.)	Length between stiffeners L_ϕ (in.)	Wall thk at 2028 (max/min) (in.)	Buckling parameters: M_ϕ	Buckling parameters: $C_{\theta r}$	Sidewall allowable vacuum (in. w.g.)
100-Series Single-Shell Tanks																								
B	0.25	13.5	6840	12	0.264	1.32	17.34	0.151	2.07	1	2.17	3.17	4.17	5.17	6.17	Lower	0.25	13.5	450	54	0.264	4.96	0.243	24.44
		72			0.163	0.50	22.07	0.147	1.28		1.32	2.32	3.32	4.32	5.32			72			0.163	6.31	0.179	6.85
										1.25	2.17	3.42	4.67	5.92	7.17	Upper	0.25	10.75			0.267	4.93	0.245	25.13
											1.32	2.57	3.82	5.07	6.32			127			0.108	7.75	0.140	2.35
C	0.25	19	6840	12	0.258	1.26	17.52	0.150	2.03	1	2.12	3.12	4.12	5.12	6.12	Lower	0.25	19	450	54	0.258	5.01	0.240	23.12
		127			0.108	0.22	27.12	0.144	0.85		0.86	1.86	2.86	3.86	4.86			127			0.108	7.75	0.140	2.35
										1.25	2.12	3.37	4.62	5.87	7.12	Upper	0.25	30			0.247	5.12	0.233	20.60
											0.86	2.11	3.36	4.61	5.86			182			0.053	11.08	0.093	0.37
T	0.25	13.5	6840	12	0.264	1.32	17.34	0.151	2.07	1	2.17	3.17	4.17	5.17	6.17	Lower	0.25	13.5	450	54	0.264	4.96	0.243	24.44
		72			0.163	0.50	22.07	0.147	1.28		1.32	2.32	3.32	4.32	5.32			72			0.163	6.31	0.179	6.85
										1.25	2.17	3.42	4.67	5.92	7.17	Upper	0.25	10.75			0.267	4.93	0.245	25.13
											1.32	2.57	3.82	5.07	6.32			127			0.108	7.75	0.140	2.35
U	0.25	35.5	6840	12	0.242	1.11	18.11	0.150	1.90	1	1.98	2.98	3.98	4.98	5.98	Lower	0.25	35.5	450	54	0.242	5.18	0.230	19.41
		127			0.108	0.22	27.12	0.144	0.85		0.86	1.86	2.86	3.86	4.86			127			0.108	7.75	0.140	2.35
										1.25	1.98	3.23	4.48	5.73	6.98	Upper	0.25	63			0.214	5.50	0.213	14.11
											0.86	2.11	3.36	4.61	5.86			182			0.053	11.08	0.093	0.37
BX	0.375	13.2	6840	12	0.389	2.87	14.27	0.156	3.06	1	3.28	4.28	5.28	6.28	7.28	Lower	0.25	13.2	450	54	0.264	4.95	0.243	24.52
		69			0.291	1.60	16.51	0.152	2.28		2.40	3.40	4.40	5.40	6.40			69			0.166	6.25	0.181	7.19
										1.25	3.28	4.53	5.78	7.03	8.28	Upper	0.25	10.6			0.267	4.93	0.245	25.16
											2.40	3.65	4.90	6.15	7.40			121			0.114	7.55	0.144	2.70
TX	0.375	18.2	6840	12	0.384	2.79	14.37	0.156	3.02	1	3.23	4.23	5.23	6.23	7.23	Lower	0.3125	18.2	450	54	0.322	4.49	0.277	41.44
		119			0.241	1.10	18.15	0.150	1.89		1.97	2.97	3.97	4.97	5.97			119			0.178	6.03	0.189	8.69
										1.25	3.23	4.48	5.73	6.98	8.23	Upper	0.25	28.4			0.249	5.10	0.234	20.95
											1.97	3.22	4.47	5.72	6.97			170			0.065	10.00	0.104	0.63
BY	0.375	18	6840	12	0.384	2.79	14.36	0.156	3.02	1	3.24	4.24	5.24	6.24	7.24	Lower	0.3125	18	450	54	0.322	4.49	0.277	41.51
		117			0.243	1.12	18.07	0.150	1.91		1.99	2.99	3.99	4.99	5.99			117			0.180	6.00	0.191	8.95
										1.25	3.24	4.49	5.74	6.99	8.24	Upper	0.25	28			0.249	5.10	0.234	21.04
											1.99	3.24	4.49	5.74	6.99			167			0.068	9.78	0.107	0.71
S	0.375	32	6840	12	0.370	2.60	14.63	0.155	2.91	1	3.11	4.11	5.11	6.11	7.11	Lower	0.3125	32	450	54	0.308	4.59	0.269	36.85
		113			0.247	1.15	17.93	0.150	1.94		2.02	3.02	4.02	5.02	6.02			113			0.184	5.93	0.193	9.48
										1.25	3.11	4.36	5.61	6.86	8.11	Upper	0.25	56			0.221	5.41	0.217	15.36
											2.02	3.27	4.52	5.77	7.02			161			0.074	9.37	0.112	0.88
TY	0.375	17.4	6840	12	0.385	2.80	14.35	0.156	3.02	1	3.24	4.24	5.24	6.24	7.24	Lower	0.3125	17.4	450	54	0.323	4.48	0.278	41.71
		111			0.249	1.17	17.85	0.150	1.95		2.04	3.04	4.04	5.04	6.04			111			0.186	5.90	0.195	9.75
										1.25	3.24	4.49	5.74	6.99	8.24	Upper	0.25	26.8			0.251	5.09	0.235	21.31
											2.04	3.29	4.54	5.79	7.04			158			0.077	9.19	0.115	0.98
SX	0.375	30.5	6840	14.875	0.372	2.62	16.26	0.152	2.92	1	3.12	4.12	5.12	6.12	7.12	Lower	0.375	30.5	450	54	0.372	4.17	0.306	61.17
		117			0.243	1.12	20.12	0.148	1.91		1.99	2.99	3.99	4.99	5.99			117			0.243	5.17	0.230	19.60
										1.25	3.12	4.37	5.62	6.87	8.12	Upper	0.375	53			0.349	4.31	0.293	51.71
											1.99	3.24	4.49	5.74	6.99			152			0.208	5.58	0.208	13.00
A	0.375	12.4	Flat	0	0.390	0	0	0	3.06	1	3.06	4.06	5.06	6.06	7.06	Lower	0.375	12.4	450	54	0.390	4.08	0.317	69.53
		61			0.299	0	0	0	2.35		2.35	3.35	4.35	5.35	6.35			61			0.299	4.66	0.264	34.02
										1.25	3.06	4.31	5.56	6.81	8.06	Upper	0.375	10.2			0.392	4.06	0.318	70.60
											2.35	3.60	4.85	6.10	7.35			105			0.255	5.04	0.238	22.27
AX	0.375	11.5	Flat	0	0.391	0	0	0	3.07	1	3.07	4.07	5.07	6.07	7.07	Lower	0.375	11.5	450	54	0.391	4.07	0.317	69.97
		52			0.308	0	0	0	2.42		2.42	3.42	4.42	5.42	6.42			52			0.308	4.59	0.269	36.82
										1.25	3.07	4.32	5.57	6.82	8.07	Upper	0.375	9.75			0.393	4.06	0.318	70.82
											2.42	3.67	4.92	6.17	7.42			87			0.273	4.87	0.248	26.70
200-Series Single-Shell Tanks																								
B, C, T, U	0.25	13.5	661	6	0.264	141.05	12.26	0.161	2.07	1	13.45	14.45	15.45	16.45	17.45	Lower	0.25	13.5	120	270	0.264	47.98	0.020	27.80
		72			0.163	53.68	15.61	0.153	1.28		5.39	6.39	7.39	8.39	9.39			72			0.163	61.09	0.015	8.26
										1.25	13.45	14.70	15.95	17.20	18.45	Upper	0.25	10.75			0.267	47.73	0.020	28.53
											5.39	6.64	7.89	9.14	10.39			127			0.108	75.07	0.012	2.94

APPENDIX

WALL THINNING OF BOTTOM AND SIDEWALL BY GENERAL CORROSION FOR SINGLE-SHELL TANKS AT THE HANFORD SITE

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INTEROFFICE MEMO

CH2MHILL
Hanford Group, Inc.

From:	Maintenance/Reliability Engineering	7G500-02-RPA-028
Phone:	373-0785	
Date:	July 18, 2002	
Subject:	WALL THINNING OF BOTTOM AND SIDEWALL BY GENERAL CORROSION FOR SINGLE-SHELL TANKS AT THE HANFORD SITE	

To:	M. A. Knight	R2-11
Copies:	V. C. Boyles	R2-11
	L. J. Julyk	R3-83
	D. H. Shuford	R3-83

Per your request, I performed an evaluation of thickness loss experienced by the bottom and sidewall of single-shell tanks from general corrosion during the period from the start of operations through the year 2002. The evaluation also includes a general corrosion rate range for future wall thinning estimates, and the effect of thermal ageing on residual stresses and elastic modulus of tank steel. The attached report describes the results of the evaluation.

Based on the current estimates, the wall thinning for the bottom and lower wall of the single-shell tanks is expected to be the same, and ranges from a low of 11.5-52 mils for the AX Farm to a high of 35.5-127 mils for the U Farm. The wall thinning for the upper wall of the single-shell tanks ranges from a low of 9.75-87 mils for the AX Farm to a high of 63-182 mils for the U Farm. A general corrosion rate range of 0.1-0.2 mil/year is recommended for future wall thinning estimates of all single-shell tanks.

It should be noted that the high temperatures experienced by the single-shell tanks would not relieve the residual stresses. On the other hand, the elastic modulus could be reduced by more than 7% by the long-term operation of single-shell tanks at high temperatures. However, if the tanks cool to room temperature because of retrieval of heat generating waste, the modulus value is presumed to increase back up to likely within 10% of the original room temperature value. Thermal ageing of single-shell tanks at high temperatures, such as those experienced by the boiling waste tanks, for a long period of time is expected to embrittle the carbon steel liner.

Should you have any questions concerning the report, please feel free to contact me at 373-0785.

Signature copy on file

R. P. Anantatmula
Principal Engineer

fam

Attachment

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7G500-02-RPA-028

Attachment

WALL THINNING OF BOTTOM AND SIDEWALL BY GENERAL CORROSION FOR SINGLE-SHELL TANKS AT THE HANFORD SITE

Consisting of 8 pages
including cover page

WALL THINNING OF BOTTOM AND SIDEWALL BY GENERAL CORROSION FOR SINGLE-SHELL TANKS AT THE HANFORD SITE

1.0 INTRODUCTION

The majority of the wastes stored in the SSTs are radioactive slurries generated by irradiated uranium fuel reprocessing using the Bismuth-Phosphate process, the reduction oxidation (REDOX) process, the plutonium-uranium extraction (PUREX) process, the tributyl phosphate (TBP) process, and the B Plant waste fractionation process. All of the fuel processing methods generated acidic waste streams. Sodium hydroxide or calcium carbonate was added to the waste before the waste was transferred to the tanks to neutralize the acid and thus minimize tank corrosion. The tanks currently contain moderately to strongly alkaline solutions, with pH values exceeding 13.

According to Hanlon (2002), 67 Hanford SSTs have been declared confirmed or assumed leakers, so it is obvious that the liners of at least some of the tanks have been breached by some mechanism. Results of SST integrity examinations reported recently (Rifaey 2002) show that some liners have significant visible corrosion, and that pitting corrosion at the liquid-vapor interface corresponding to prior liquid levels appears to have perforated the liners of some tanks. A few tanks with self-boiling wastes have experienced bulges in the bottom of the liners. This is thought to be due to expansion of steam underneath the liner. The stresses induced by the bulges, in combination with existing corrosion-induced liner degradation, is another mechanism that may have resulted in breaches of the liners. On the other hand, photographs and videotapes of many SST liners show that the liners appear to be in very good condition. That is, there is very little visible evidence of significant general corrosion. Although general corrosion always occurs, it does not usually lead to failure of industrial systems. Ultrasonic inspection of tank wall and bottom of non-stress relieved tanks at SRS indicated very little general wall thinning in ten years of testing. Therefore, the breach of the 67 SSTs presumably occurred by either pitting or stress corrosion cracking (SCC) or a combination of both mechanisms.

This report includes an evaluation of thickness loss experienced by the bottom and sidewall of single-shell tanks (SSTs) from general corrosion during the period from the start of operations to year 2002. The evaluation also includes the effect of thermal ageing on residual stresses and elastic modulus of tank steel for those tanks that stored self-boiling wastes for a long time period. Because of the time constraint, each of the 149 tanks is not evaluated separately, as was done previously for SSTs 241-C-104 and 241-C-106 (Anantatmula 2001b,c). The basis of the evaluation and the results are described in detail in the following.

2.0 EVALUATION BASIS

Because this is a larger effort than the evaluations made for SSTs 241-C-104 and 241-C-106, and there are no data available in the literature that are truly representative of corrosion of carbon steel wall of SSTs exposed to the waste environment, a different approach was used compared to the previous evaluation methodology. Each SST tank farm has been identified with a primary

waste type, which is present in the majority of tanks in the tank farm. According to the SORT model analyses of Hill et al. (1995), the primary waste types present in the 100 series SSTs are bismuth phosphate ($BiPO_4$) waste, tri-butyl phosphate (TBP) waste, REDOX waste, evaporator bottoms (EB) waste and double-shell slurry feed (DSSF). The primary waste types in the 200 series SSTs are lanthanum fluoride decontamination (224) waste, hot semi-works (HS) waste and cladding waste (CW).

In the 1950s, during the initial stages of SST operations, when the tanks were at or close to their highest temperatures, in-tank corrosion coupon experiments were performed in some tanks along with laboratory tests with simulated wastes. For this analysis, the in-tank corrosion data from coupons exposed in the SSTs were used as a basis. This is because the in-tank coupon test conditions are more prototypic of the actual tank conditions and it is very difficult to simulate the in-tank environment using the laboratory equipment, which is on a much smaller scale. If only laboratory data on simulated wastes were available, those data were used instead. However, in view of the fact that the pH of the SST wastes is in the range 7-13, only laboratory data on simulated waste solutions of pH$\geq$7 were used. In the absence of in-tank and laboratory data for a given primary waste type, the corrosion data for the primary waste type with a corrosivity factor (CF) close to the CF (Anantatmula et al. 1994) of the primary waste in question was used. On this basis, the general corrosion behavior for EB waste was assumed the same as that for the TBP waste, and the general corrosion behavior of DSSF, 224, HS and CW was assumed to be similar to that of $BiPO_4$ waste

Table 1 gives the general corrosion rate data for single-shell tanks on the basis of the primary waste type stored in each tank farm and the assumed ranges of general corrosion rate.

TABLE 1
IN-TANK GENERAL CORROSION RATE DATA OF SINGLE-SHELL TANKS

PRIMARY WASTE TYPE	GENERAL CORROSION RATE IN LIQUID (MILS/YEAR)		GENERAL CORROSION RATE IN VAPOR SPACE (MILS/YEAR)	
	IN-TANK DATA	ASSUMED RANGE	IN-TANK DATA	ASSUMED RANGE
$BiPO_4$	0.1[a]	0.1-1	0.05-2[a]	0.05-2
REDOX	0.5[b]-0.8[c]	0.5-2	1[c]	1-3
TBP	0.2[d]	0.2-2	0.4-0.6[d]	0.4-3
EB	NDA	0.2-2[e]	NDA	0.4-3[e]
DSSF	NDA	0.1-1[f]	NDA	0.05-2[f]
224	NDA	0.1-1[f]	NDA	0.05-2[f]
HS	NDA	0.1-1[f]	NDA	0.05-2[f]
CW	NDA	0.1-1[f]	NDA	0.05-2[f]

TBP = Tri-butyl Phosphate Waste; EB = Evaporator Bottoms Waste
DSSF = Double-Shell Slurry Feed; 224 = Lanthanum Fluoride Decontamination Waste
HS = Hot Semi-Works Waste; CW = Cladding Waste
NDA = No data available
[a]Endow (1954); [b]Mallett (1954); [c]Gruber (1957)
[d]Laboratory data; No in-tank data available; Groves (1953, 1954)
[e]Assumed same as TBP; [f]Assumed same as $BiPO_4$

As can be seen from Table 1, the assumed general corrosion rates are higher in vapor space than in liquid. This is consistent with the fact that the liquid waste environment is more inhibited compared to the high humidity vapor space environment. The higher corrosion rates in the vapor space are also supported by the results from the most recent analysis of corrosion probe coupons retrieved from double-shell tank 241-AN-107 (Anantatmula 2001a).

3.0 RESULTS OF EVALUATION

3.1 WALL THINNING THROUGH YEAR 2002

The assumed ranges of general corrosion rates from Table 1 were used to estimate the ranges of general corrosion depths for SST tank farms to year 2002 since the beginning of tank operations. Table 2 summarizes the results of the evaluation of general wall thinning of bottom and sidewall for all the tank farms. Also included in these estimates is the general corrosion damage depth experienced by the SSTs by the hydro-test water stored in the tanks prior to start of operations. It was assumed that the water was stored for a period of 4 years in each tank prior to start of operations. A general corrosion depth of 8-17 mils was calculated for all the tanks using aqueous corrosion model available in the literature (Lee at al. 1996). This general corrosion depth is common to the tank bottom as well as the sidewall.

The results include a high and a low value for general corrosion depth in each case. Tank sidewall corrosion is categorized into two parts, viz., lower wall and upper wall. The lower wall is defined as the location where the wastes are contacting the carbon steel liner. The upper wall is assumed to have been in contact only with the vapor space environment at any time.

As can be seen from Table 2, the wall thinning for tank bottom and lower wall is the same because it was assumed that the availability of oxygen is limited at the bottom as well as throughout the majority of the lower wall. The wall thinning for the bottom and lower wall ranges from a low of 11.5-52 mils for the AX Farm to 35.5-127 mils for the U Farm. The wall thinning for the upper wall ranges from a low of 9.75-87 mils for the AX Farm to 63-182 mils for the U Farm.

3.2 FUTURE WALL THINNING

Because overall SST inventories of corrosion inhibitors, viz., NO_2^- and OH^-, increased in time relative to the primary corroding agent, NO_3^-, the general corrosion rate (including other forms of corrosion) is expected to decrease as a function of time. More recently, a liner general corrosion rate of 0.2 mils per year (mpy) was estimated for the current condition of the SSTs (Anantatmula 1999), which was supported by the hydrogen inventory measured in the dome space of the SSTs. These estimates also yielded 0.1 mpy for the DSTs. Therefore, a general corrosion rate range of 0.1-0.2 mpy is recommended for future wall thinning estimates of all SSTs.

TABLE 2
GENERAL CORROSION DEPTH ESTIMATES FOR SINGLE-SHELL TANKS

TANK FARM	CONSTRUCTION DATE	PRIMARY WASTE	GENERAL CORROSION DEPTH TO 2002 (MILS)			ASSUMPTIONS
			BOTTOM	LOWER WALL	UPPER WALL	
100 SERIES TANKS						
B	1943-44	$BiPO_4$	13.5-72	13.5-72	10.75-127	Assumed a general corrosion damage depth of 8-17 mils during water storage (assumed to be 4 years duration) prior to start of operations for all tanks including the 200 series. Corrosivity of EB and DSSF assumed to be the same as that of TBP and $BiPO_4$ respectively.
C	1943-44	TBP	19-127	19-127	30-182	
T	1943-44	$BiPO_4$	13.5-72	13.5-72	10.75-127	
U	1943-44	REDOX	35.5-127	35.5-127	63-182	
BX	1946-47	$BiPO_4$	13.2-69	13.2-69	10.6-121	
TX	1947-48	EB	18.2-119	18.2-119	28.4-170	
BY	1948-49	TBP	18-117	18-117	28-167	
S	1950-51	REDOX	32-113	32-113	56-161	
TY	1951-52	TBP	17.4-111	17.4-111	26.8-158	
SX	1953-54	REDOX	30.5-117	30.5-117	53-152	
A	1954-55	DSSF	12.4-61	12.4-61	10.2-105	
AX	1963-64	DSSF	11.5-52	11.5-52	9.75-87	
200 SERIES TANKS						
B	1943-44	224	13.5-72	13.5-72	10.75-127	Corrosivity of 224, HS and CW assumed to be the same as that of $BiPO_4$.
C	1943-44	HS	13.5-72	13.5-72	10.75-127	
T	1943-44	224	13.5-72	13.5-72	10.75-127	
U	1943-44	CW	13.5-72	13.5-72	10.75-127	

TBP = Tri-butyl Phosphate Waste
EB = Evaporator Bottoms Waste
DSSF = Double-Shell Slurry Feed
224 = Lanthanum Fluoride Decontamination Waste
HS = Hot Semi-Works Waste
CW = Cladding Waste

3.3 EFFECT OF LONG-TERM OPERATION AT HIGH TEMPERATURES ON MECHANICAL PROPERTIES

The following paragraphs discuss the effect of thermal ageing on residual stresses, elastic modulus and ductility.

Relief of residual stresses is a time-temperature related phenomenon. The thermal effect on residual stresses is usually expressed by the Larson-Miller (L-M) parameter (ASM 1985) as

$$P = 1.8T(20+\log t)10^{-3}$$

where P is the L-M parameter, T is temperature in ^{0}K and t is time in hours. Residual stresses in carbon steel are generally relieved by heating the steel to 1100^{0}F and maintaining the temperature for at least 1 hour. In order to obtain the same effect at 600^{0}F (the approximate maximum temperature seen in the SSTs), the time required from the above equation is 2.73 x 10^9 hours, which is several orders of magnitude larger than 60 years (the approximate age of the oldest SSTs). Therefore, it can be very easily concluded that the high temperatures experienced by the SSTs will not relieve the residual stresses.

As far as the elastic modulus is concerned, raising the temperature of carbon steel lowers its elastic modulus (ASM 1985). If we assume that the thermal effect on Young's modulus can also be expressed as a time-temperature related phenomenon, then the effect of ageing on elastic modulus can easily be calculated using the L-M parameter equation above. Temperature history is well documented only for the high heat tank 241-C-106. This tank had been exposed to boiling temperatures for approximately 10 years with a maximum temperature recorded at 310^{0}F. Based on the above equation, the thermal effect of ageing the carbon steel at 310^{0}F for 10 years is equivalent to performing a modulus test for 1 hour at 500^{0}F. The net thermal effect would be an approximate 7% reduction in elastic modulus (ASM 1985) compared to the instantaneous value at 310^{0}F, which is not significant. The modulus reduction could be higher for those tanks with higher maximum temperatures maintained for a long period. However, if the tank cools to room temperature because of retrieval of heat generating waste, the modulus value is presumed to increase back up to likely within 10% of the original room temperature value.

Thermal ageing of SSTs at high temperatures, such as those experienced by the boiling waste tanks, for a long period of time is expected to embrittle the non-stress- relieved carbon steel liner by a loss in ductility; this phenomenon is called strain aging or strain age embrittlement.

4.0 CONCLUSIONS

Based on the current estimates, the wall thinning for the bottom and lower wall of the SSTs is expected to be the same, and ranges from a low of 11.5-52 mils for the AX Farm to a high of 35.5-127 mils for the U Farm. The wall thinning for the upper wall of the SSTs ranges from a low of 9.75-87 mils for the AX Farm to a high of 63-182 mils for the U Farm. A general corrosion rate range of 0.1-0.2 mpy is recommended for future wall thinning estimates of all SSTs.

It should be noted that the high temperatures experienced by the SSTs will not relieve the residual stresses. On the other hand, the elastic modulus could be reduced by more than 7% by the long-term operation of SSTs at high temperatures. However, if the tanks cool to room temperature because of retrieval of heat generating waste, the modulus value is presumed to increase back up to likely within 10% of the original room temperature value. Thermal ageing of SSTs at high temperatures, such as those experienced by the boiling waste tanks, for a long period of time is expected to embrittle the non-stress- relieved carbon steel liner by a loss in ductility; this phenomenon is called strain aging or strain age embrittlement.

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